

# Empirical Measurements of Intrabody Communication Performance under Varied Physical Configurations

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## ABSTRACT

Intrabody communication (IBC) is a wireless communications technology that uses a person's body as the transmission medium for imperceptible electrical signals. Because communication is limited to the vicinity of a person's body, ambiguities arising from communication between personal devices and environmental devices when multiple people are present can, in theory, be solved simply. Intrabody communication also potentially allows data to be transferred when a person touches an IBC-enabled device. We have designed and constructed an intrabody communication system, modeled after Zimmerman's original design, and extended it to operate up to 38.4Kbps and to calculate signal strength. In this paper, we present quantitative measurements of data error rates and signal strength while varying hand distance to transceiver plate, electrode location on the body, touch plate size and shape, and several other factors. We find that plate size and shape have only minor effects, but that the distance to plate and the coupling mechanism significantly effect signal strength. We also find that portable devices, with poor ground coupling, suffer more significant signal attenuation. Our goal is to promote design guidelines for this technology and identify the best contexts for its effective deployment.

**KEYWORDS:** Ubiquitous computing, wearable computing, input devices, hardware, mobile interfaces

## INTRODUCTION

Intrabody Communication (IBC) [13] is a new way for electronic devices to communicate with each other. Rather than connecting them by wire or transmitting a radio signal, IBC uses the human body to conduct an imperceptible electrical signal. Devices send and receive the signal using *dry elec-*

*trodes*: conductive surfaces of several square centimeters in close contact with the skin.

Although only a few prototype IBC systems have been constructed, broad deployment of IBC could significantly change how people interact with the world.

One application area is Personal Area Networks [14]. IBC would allow several wearable devices carried by one person to exchange information and share I/O hardware resources such as speakers and microphones. Power would be saved, and devices could be made smaller. Communication between wearables also allows applications to eliminate cumbersome wiring, as is done in the FingerRing [3].

IBC can also be used to communicate between wearables and devices in the environment. A person's identity, access privileges, or other customization information can be transmitted to unlock doors, annotate digital photos, or tailor TV entertainment [8]. People can electronically exchange business cards through a handshake [14]. Keyboards and displays in the environment can allow more comfortable user interfaces to wearables [10].

More sophisticated interactions between environmental devices and wearables are also possible. Context-aware environments, such as Labscape [2] and the Aware Home [7], could notice which devices a user touches, as well as any actions taken with those devices. These events would augment the *touch events* of Hinckley, et al. [6] with data transmission to and from the personal device carried by the user. Collected information from many events could be used to construct a model of user behavior. This model could then be used to customize user interface interactions according to the operations the user is predicted to perform.

Much of this functionality could be accomplished with existing technologies, such as short-range radio or infrared communication. However, IBC has an advantage: the signal strength falls off very quickly with distance from the trans-

mitter or person [14]. Radio signal power drops with the square of distance; IBC drops with the cube of distance. The signal is therefore more difficult to intercept, which is desirable for secure transmissions. The signal is also more isolated from IBC signals generated by transmitters carried by other people. Furthermore, no ambiguities arise when an environmental device tries to contact the wearable of the user touching the environmental device's UI. Only wearables of the correct user can be contacted; other wearables are out of range.

IBC has faced some problems that have prevented its widespread adoption. Among them are: low bandwidth, severe signal attenuation, a large number of design parameters, and health concerns.

Low bandwidths were characteristic of the first IBC systems. Zimmerman's original system ran at 2400 bps. Subsequent systems from the MIT Media Lab ran at 9600 [9], as did Matsushita's Wearable Key [8]. However, as Zimmerman points out, the theoretical limit approaches hundreds of kilobytes per second.

A second major problem is signal attenuation. Starting from a transmitter voltage of 20V, the received signal strength might be attenuated to the nanovolt or even picovolt range, making reception very difficult.

IBC requires a complete circuit to function. The person provides one link in the circuit, but a second conductive path, the "return path", is necessary to complete it. The return path flows by either capacitive coupling through air [3, 8], or through two "air couplers" and a conductive object such as earth ground [14]. The capacitance of air couplers is extremely small: on the order of femtofarads [14]. Weak signals in IBC systems are generally due to a poor return path, not a lack of conductivity through the human body.

Three common configurations have been developed to accommodate the air-coupling attenuation problem. One is to locate the electrode on a foot and a return-path plate on the underside of a shoe to couple to earth ground. Then any other device with a good earth ground connection has a strong return path. A second configuration is to locate the device on a wrist. A return-path plate set off from the wrist provides a good return path as long as it is relatively close enough to another conductive surface on the other transceiver. A third configuration is to build the plates into a belt to provide a large surface area.

When we first looked at IBC, we had questions about all three approaches. Although shoe-coupling works well with other grounded devices, we did not know whether the air coupling was strong enough to communicate with portable devices. Wrist-coupling could couple to portable devices, but it wasn't clear whether a device could communicate when touched with the opposite hand. We also were curious about the relationship between electrode and plate size and received

signal strength. Belt coupling looked convenient, but it wasn't clear if the return path plate could be set far enough out from the body to be effective.

The third major problem IBC faces is a large number of design variables. In addition to coupling location, other factors such as electrode size, transmit voltage, receive gain, most effective frequency, noise sources, and other interfering transmitters affect the overall system performance. The effect of all these parameters is not well understood.

Finally, there are health concerns. While short-term electrical damage (e.g. shock) is unlikely in a well designed system, the long-term effects of electric fields are unknown. Many epidemiological studies have been performed to search for a link between electrical and magnetic fields and cancer, but the results have been inconclusive. IBC operates at different frequencies and strengths from most studies, which look at fields from power lines and cell phones. IBC does operate within standard government safety guidelines, inserting less energy into the human body than certified commercial pain-relief electrical stimulators. A literature review of various studies can be found in [5].

This paper describes the performance of our IBC implementation. We examine variations in electrode coupling location, plate size, geometric variations, and several other factors. We also report on the performance when multiple interfering transmitters are present to determine the ability to work well with multiple simultaneously active people and devices. We do not address the health concerns in this paper.

Although our primary goal is not a high-bandwidth design, we have developed a prototype system that achieves 38.4Kbps. Our implementation appears to be limited by the communications hardware, and not by the human body channel. Faster data rates should be achievable with more careful transceiver design.

## IMPLEMENTATION

Figure 1 shows a basic circuit model for an IBC system. In our implementation, each device is capable of both transmission and reception, however to simplify this explanation, the circuit contains only a single transmitter and receiver. Each device has two plates; one is an electrode, which couples to the human body. The other is the return path plate. Throughout this paper, we consider only the case where one device is a *personal device*; it is carried by the person at all times, and never tethered to the environment.

### Frequencies

By using a high enough frequency, the effects of the small capacitances can be eliminated, however at too high, the electric and magnetic fields couple, and produce electromagnetic radiation that does not remain confined to the human body.

The range of frequencies in which IBC can operate is limited. As the signal frequency increases, the wavelength shortens.

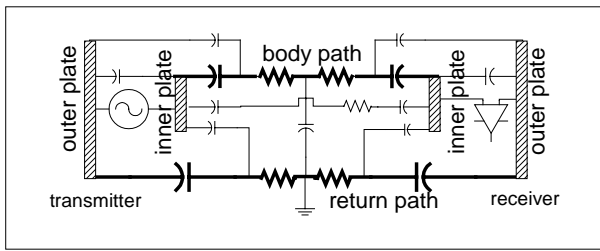


Figure 1: Basic circuit model of system. The transmitter generates an AC voltage across two plates, and the receiver picks it up.

At 300 MHz, the wavelength is 1 meter, roughly the same size as a person. At such speeds, the person behaves electrically as an antenna, radiating the signal into space rather than conducting it to touched items. To avoid this affect, Zimmerman suggests limiting frequencies to 1 MHz [8].

Systems at such frequencies are termed *quasi-electrostatic*. Although they involve changing voltages and currents, the fields change slowly enough that they can be analyzed in the same way as electrostatic systems. A simple electrostatic model for an IBC transmitter is a dipole. At far enough distances, the strength of the surrounding electric field decreases with the cube of the distance from the dipole center. When a conductive object such as a person is placed in the field of a dipole, the field is distorted. When a person touches a transmitter, the distorted field causes the voltage difference across the receiver plates to increase.

At the frequencies IBC uses, the human body behaves as a moderate resistor, around 10k $\Omega$  to 100k $\Omega$ . The air-coupling capacitors are very small, between 10fF and 500pF depending on their sizes, positions, and orientations. These capacitances are small enough that other air capacitances between circuit elements (shown in gray in Figure 1) affect the performance of the system by reducing the signal further.

### Physical Design

The plates are made from various conductive materials such as aluminum foil, copper tape, and a woven stainless steel fabric. Stranded copper wire connects the boards to the plates. The wire is soldered to the board, and firmly meshed into each plate using copper tape.

We constructed three body-coupling plates: a belt, a wrist strap, and a shoe. We also added plates to a PDA to get a sense for how well the system would perform with a portable device (see Figures 2–5).

### Transceiver Electronics

The transceiver contains three separate parts. The physical layer handles signal amplification and transmit/receive multiplexing. The encoding layer modulates and demodulates the signal from analog frequencies to digital data. The applications layer controls what is sent to and from the digital layer. We have implemented a preliminary link layer for reli-

Object	Electrode	Return Path Plate	Material
Belt	100 cm <sup>2</sup>	100 cm <sup>2</sup>	Copper tape
Shoe	250 cm <sup>2</sup>	250 cm <sup>2</sup>	Aluminum Foil
Watch	15 cm <sup>2</sup>	15 cm <sup>2</sup>	Copper tape
PDA	30 cm <sup>2</sup>	14 cm <sup>2</sup>	Copper tape
Test plates	25 cm <sup>2</sup> to 225 cm <sup>2</sup> in increments of 25 cm <sup>2</sup>		Aluminum foil

Figure 2: Objects and their coupling plate sizes

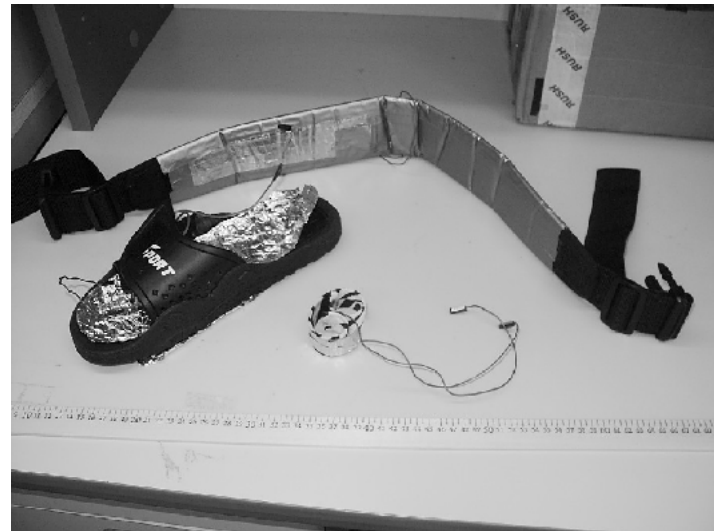


Figure 3: Belt, wrist strap, and shoe

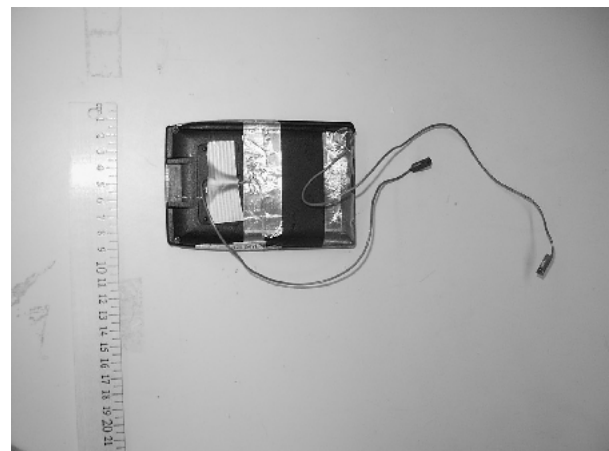


Figure 4: PDA

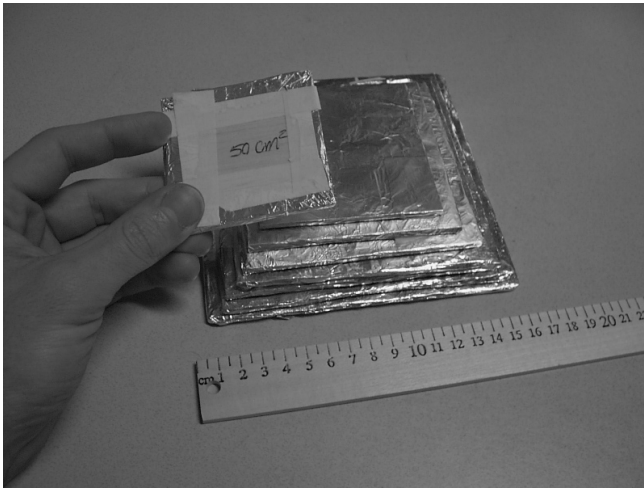


Figure 5: Various sized plates

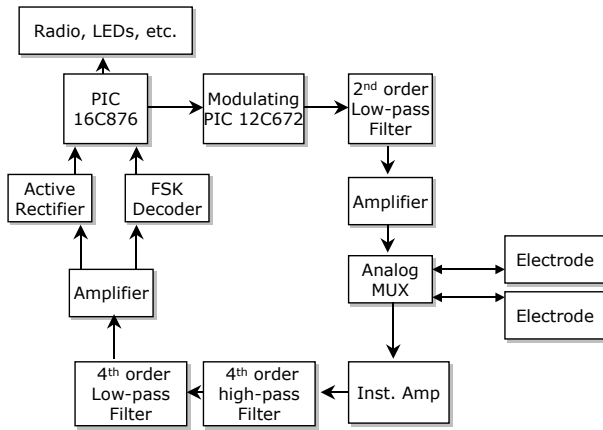


Figure 6: Circuit High-Level Schematic

able data transmission, but did not use it to collect the results in this paper.

### Data Encoding

We encode digital signals using Frequency Shift Keying (FSK). In this scheme, a different frequency is chosen to send a “0” bit and a “1” bit. This scheme is simple to implement and is fairly noise-resistant. We use 180 kHz and 140 kHz. The fastest data rate we have achieved with under 5% error rate using FSK and these frequencies is 38.4kbps. Beyond that, the data rate is too close to the signal frequencies to be accurately decoded.

Figure 6 shows a schematic of the circuit. The transmitter is on top; the receiver on the bottom. We use sharp filters to limit the noise that’s received out of bandwidth of interest. Otherwise, large 60Hz signals from power might reduce the circuit sensitivity.

Previous designs reported a maximum implemented speed of 9600 bps; our improvements are mostly due to the use of a phase-locked-loop FSK decoder chip (XR2211), which has

less jitter than the tone decoders chips used in other designs. However, we believe that the bandwidth and signal strength are sufficient that more sophisticated encoding schemes, such as those used by modems to achieve 56kbps in 3kHz of phone-line bandwidth, could be used to achieve data rates over a megabit per second.

### Operation

Data generated from a microcontroller is modulated to a square-wave of higher frequency by a second microcontroller. It is then passed through a second-order Chebyshev filter to make a more sine-wave like signal. Without this kind of filtering, harmonics could conceivably generate noise at higher radiated frequencies. The signal is then amplified to an tunable amplitude up to 22V. A wide transmit voltage swing is needed to maximize the signal seen at the receiver.

To power the device, we used four 9V batteries, regulated to positive and negative 12V. Significant regulation is necessary because the op-amps in the signal strength measurement circuit are sensitive to power-line variations at the IBC frequencies. In an earlier design, we used a switched capacitor charge pump to generate a wider voltage swing, but we found that this generated significant switching noise that interfered with the receive circuitry. A more carefully designed system could avoid these noise problems and use a more conventional battery supply.

The receiver is the most sensitive part of the circuit. The input wires pass through two analog switches that connect the electrodes either to the transmitter or the receiver, and then to an instrumentation amplifier. The instrumentation amp boosts the power of the signal and removes interference from other electrical fields that affects both the electrode and return path plate (such as fields from wall power lines). We originally had used an INA128 for this purpose, but found that its slew rate limited amplification at higher frequencies, so we switched to the faster INA110.

Next the signal passes through two 4-pole filters which remove signals outside the transmitter frequency range, and then to the decoder chip which sends the recovered digital signal to the microcontroller.

Other designs have generated the wider voltage by a LC tank circuit. Although using a tank circuit is more power efficient, ours is optimized to give more accurate signal strength measurements and to allow sharper filters to be used on the input.

### EXPERIMENTS

We measured two different quantities in our experiments: signal strength, and data rates. Signal strength measures the amount of energy present in IBC frequencies and determines the ability of the physical layer to communicate a signal. The data rate measures the performance of both the physical layer and the encoding layer. Since many different (and more sophisticated) encoding layers could be constructed, we primarily measured signal strength to keep our results general.

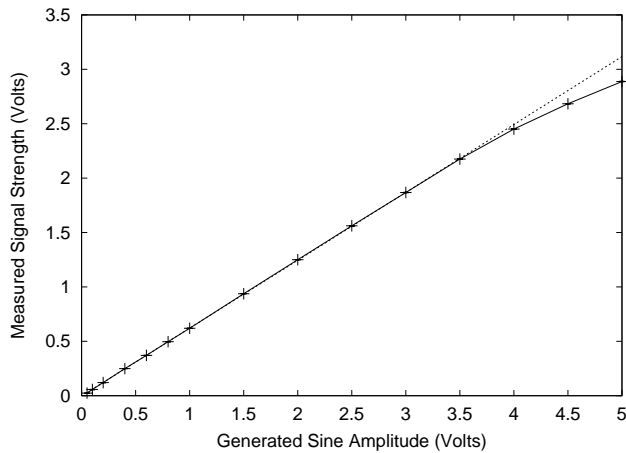


Figure 7: Calibration of the Signal Strength Circuit

However, a strong signal is of little value unless it is strong enough to carry data.

Generally speaking, measured values showed a lot of local precision, however repeated scenarios measured after performing other experiments often gave differing results, sometimes up to a factor of ten.

#### What Signal to Measure

Measuring the signal strength of this system is difficult. A standard oscilloscope cannot measure the received signal strength directly because even  $1M\Omega$  probes have too low an impedance. Electrometers have very high input impedances, however they generally cannot measure frequencies in the ranges that IBC uses.

The signal output from the preamplifier could be measured with an oscilloscope, however the output might contain noise from other sources. Several electronic devices, including fluorescent lights and computer monitors generate signals that are present in the preamplifier output. A more accurate measurement can be taken following the filtering stages that remove many of these signals.

However, the filtering stages affect the signal amplitude. The relationship between the measured signal strength and the voltage of a signal on the receiver electrodes is very linear, as shown in Figure 7. The x-axis shows the voltage of an FSK-sine wave between 140 kHz and 180 kHz switching at 20 kHz. The relationship is linear until about 3.5V. Beyond this point, saturation of the signal during the filtering stages clips the signal and distorts the linearity of the signal strength measurement. In the experiments below, all signal strength measurements are under 3.5V, so we convert them to what the voltage must have been at the receiver electrodes.

#### Measurement Grounding Issues

Measurement with an oscilloscope is also problematic for another reason, that they require establishing a common ground between the transceiver and the scope. Since the scope is



Figure 8: Basic Testing Setup

grounded to the wall current, grounding the receiver can allow some of the return path signal to flow through the grounding wire, producing unfairly positive results that would not be present if the receiver were a wearable device.

We decided that the best approach would be to include a signal-strength measurement circuit on the transceiver. The circuit consists of a half-wave active rectifier followed by a low-pass filter. Its output is digitized by the PIC's A/D converter. It is then transmitted over a 916.5 Mhz short-range radio [1] to a PC. To verify that the radio transmission did not affect the measured signal strength, we compared oscilloscope measurements when the radio was connected and when disconnected, and found no difference.

#### Physical Setup

Our measurements were primarily variations upon a single basic setup, shown in Figure 8. A transmitter with two 50 cm<sup>2</sup> plates were used on 90cm tall desk in a electronics laboratory. The desk was not a static-free desk. Static-free desks are usually found only in electronics laboratories. Our initial experiments with static-free desks indicated that they have very different characteristics than conventional desks because of their conductive nature. We set the plates upon a 17cm cardboard box to further isolate the electronics from the effects of the desk. The transmit voltage was set at 20 Volts.

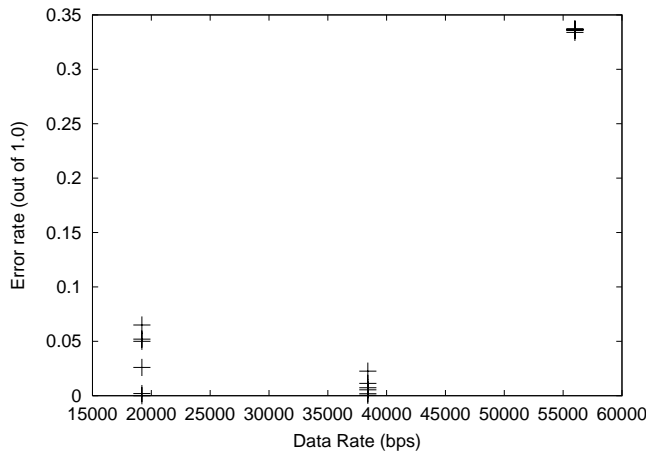


Figure 9: Signal strength v. error rate

The other transceiver was attached to a subject (the first author), 6'2", 185 lb., by one of the three body-coupling methods described previously. Generally, the subject stood approximately 10 cm from the desk, and touched one of the electrodes lightly.

For each test performed, the results were averaged over at least five measurements.

#### Data Rate

The minimum signal amplitude required by our system for decoding data is about 10mV. Below that, the bit error rate rises quickly. Note that this minimum is an artifact of the FSK decoder chip that we use; better performance may be possible.

Figure 9 shows how the error rates increase with increasing speed. The error rate is calculated by monitoring a series of increasing counters sent during a three second interval. A byte received that is one more than the previous byte is counted as correct; all other received bytes are counted as incorrect. These data rates are the best that could be achieved after careful tuning of the transmitter, and monitoring the signal strength to keep it at a large value. The unusually small variance around 56kbps in the upper right hand corner indicates that a synchronization error may be occurring because of components unable to keep pace with the data rate.

#### Body-coupling location

Zimmerman noted in his thesis [13] that performance is likely to vary depending upon the location that the electrodes couple to the body. Depending upon the location and artifact, various couplers have different sizes, proximities to earth ground, and capacitances between the inner and outer plates.

Figure 10 compares coupler performances for both the basic setup, and holding the PDA. The shoe performs significantly better than either the wrist or belt because of its natural earth ground coupling.

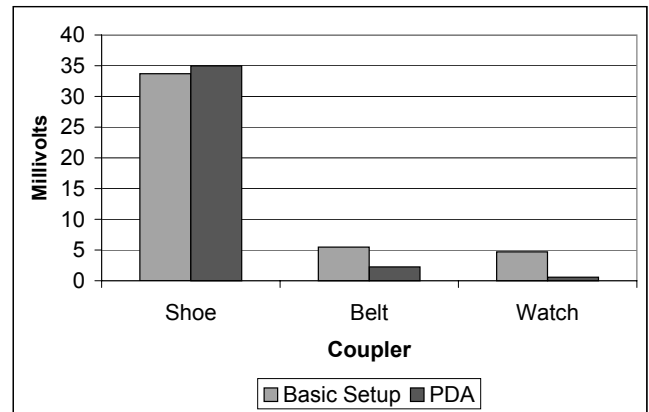


Figure 10: Variation of signal strength with coupler

Notice also that the PDA performs worse in the belt and watch cases, but comparably in the belt case. The shoe's much stronger coupling to earth ground means that the smaller fields generated by the PDA's smaller, closer together plates are not as affected. The wrist and belt are more sensitive because they couple through free space. If the ground plate in the basic setup is connected to a large (1500 cm<sup>2</sup>) plate on the floor, then the size of the free space field becomes much larger, and the received signal strength increases by a factor of three. Although this is something that can be done with most portable devices, for devices in a fixed location connections to large conductive surfaces can be very helpful.

Signal strength is also affected by the relative positioning of the plates when free-space coupling is dominant. As the PDA is bent back toward the wrist, the signal strength nearly triples. If the PDA is held in the other hand with the outer PDA plate waved near the outer wrist plate, the signal strength increases by a factor of six. However, the signal read using the hand the IBC system is not coupled is 2-10 times weaker than the hand with the coupler, depending on the proximity of the other hand.

In all cases, the signal strength is above the minimum necessary for communication. The greater signal strength of the shoe configuration means that fewer data errors and/or a greater bandwidth are possible, since it has a higher signal-to-noise ratio. However, the shoe signal drops as the person raises their foot. Raising the shoe one centimeter off the ground reduces the signal amplitude by 40%. Raising the shoe one foot reduces the signal amplitude by 85%.

#### Plate Sizes

An important design constraint is the minimum plate size needed for adequate communication. In conducting the experiments to answer this question, we found a large variability in repeated measurements as the couplers were exchanged. This appears to arise from the positions of the wires connecting the plates to the circuitry; because they conduct the very high impedance signal from the plates, they

are very susceptible to noise, and the circuit itself provides plenty. However, we did find that signal strength was generally maintained, even as foot-based coupling plates were reduced to a few cm<sup>2</sup>. More study of this issue is needed.

### **Touch-selective communication**

For some applications, it is desirable that communication be limited to situations where the user is physically touching the electrodes of both devices. With this ability, haptic feedback helps users know whether data has been transferred. Without this ability, IBC is functionally much more like a short-range radio.

Ideally, touch-selective communication would be assured by setting the transmitter power and receiver sensitivity to trimmable, but fixed levels. However, the variation in noise levels from various sources and signal strength from variables such as body position and conductive surfaces makes this infeasible.

One promising approach is to provide more power on the transmitter side than is necessary, but to reject received data when the signal strength is below a certain level. The level can be changed dynamically to compensate for changing conditions, since they change more slowly than the rapid increase in signal strength associated with physical contact.

Another way to implement touch-selective communication is to augment IBC with an alternative touch-sensing technology. This could take the form of a conventional push button, a vibration sensor or accelerometer, or a capacitive sensor. Only when touch is detected through these other mechanisms is data passed through.

An issue that arises with this solution is ambiguity when multiple people are present. Because the sensor must be associated with an object, when it is triggered, communication from all nearby IBC transceivers will be enabled, whether they belong to the person touching the object or not. However, by implementing a collision-based link-layer protocol on top, and measuring the signal strength of each received packet, the proper device can be identified.

We have implemented a prototype of an vibration-based detector. Unfortunately, it too is difficult to tune: if set too sensitively, then the device believes that touch has occurred if the user only bumps the table. If not sensitive enough, then if the user is fairly still then sensor thinks that the device has been put down. We are currently investigating ways to improve the sensor's sensitivity and process the signal more carefully.

### **Multiple People**

To verify that a receiver could distinguish between two separate transmitters, we constructed a test scenario with one transmitter broadcasting an increasing loop counter, and the other a decreasing loop counter. The receiver lit a LED if increasing numbers were received, and sounded a buzzer for decreasing numbers. When two subjects stood in front of the device, it favored one over the other, although the signal ap-

peared to be noisy (the LED flickered or the tone scratched). However, when one subject touched the electrode, the appropriate individual was identified.

More comprehensive studies of multiple people are needed. It is important to determine the effectiveness of various physical layer encoding schemes under various conditions. FSK is relatively immune to interfering noise (the strongest signal wins), however it is limited in bandwidth. Finding the right tradeoff is an interesting research problem.

### **Other Observations**

Various other effects were observed in the process of our experiments. We suspected that the superior performance of the shoe might have been because of a person's weight pressing down. However, in other experiments, pressure did not seem to make much difference. We also performed a few experiments with another subject to determine if individual differences affected performance, but the results were identical to the first user. We ran a few tests to see if gloves would affect the system performance; surgical gloves made little difference, but ski gloves reduced signal strength by 40%.

Finally, we tested the the wrist coupler while barefoot, and found very little difference from the basic setup. This was a little surprising, because we thought that having a better connection between the person and the laboratory floor would significantly shunt the signal. Perhaps most of the signal strength seen by the wrist-coupled receiver

### **FUTURE WORK**

One issue we plan to investigate in the future is the usable frequency range; some implementations have operated up to 14 MHz [8], so there may be enough bandwidth present to compete with new short-range wireless data-communication standards.

Another interesting technique is the use of shielded plates. All of our plates are bare conductors. By driving a second conductor at the voltage of the first plate, a plate can be made essentially "one-sided", and more sensitive to the signals on the body or the air-coupled return path.

We also intend to add an automatic gain control circuit in future designs to avoid saturation problems and extend the dynamic range of the circuit.

Finally, more investigation needs to be done to determine the potential health hazards of this technology.

### **CONCLUSIONS**

We have constructed an reimplement of IBC, and performed many measurements to determine its performance under various circumstances. Signal strength from the shoe is much stronger than from the wrist or belt. Making communication touch-selective is very challenging; because the plates can couple in ways other than through the body, communication often happens even when a person is not touching

electrodes on both devices. We believe that a hybrid sensor approach may provide a promising direction for solving this problem.

Although many challenges remain in understanding and engineering the technology, we believe it is a compelling mechanism that could be used in future ubiquitous computing scenarios.

#### ACKNOWLEDGEMENTS

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